Local Connection Failures in Composite Sandwich Panel Systems

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ABSTRACT

The use of sandwich panels in the Australian building industry has increased rapidly over the past few years. Sandwich panels used in Australia typically comprise of expanded polystyrene foam core and thin steel faces. Although the past research in Europe and the USA has made significant advances to the structural behaviour and design of sandwich panels during the last three decades, there is lack of knowledge and design information on the pull-through failure of connections in sandwich panels. This research project was therefore undertaken to gain an understanding of the pull-through behaviour of sandwich panel connections using experimental studies. It was found that a number of other parameters including foam core characteristics influenced the pull-through strength in addition to the primary parameters of washer diameter, face thickness and strength. An interim design equation was developed for the pull-through strength of connections by including all the relevant parameters. This paper presents the details of this research project and the results obtained to date.

INTRODUCTION

Sandwich panels used in the Australian construction industry typically comprise of expanded polystyrene foam core sandwiched between two thin steel faces (Figure 1). They are available as flat, lightly profiled or fully profiled panels. Their use in this industry has increased rapidly over the past few years, primarily due to their lightweight nature, structural and energy efficiencies and aesthetic merits. Due to this increase in usage in Australia, Europe and the USA, research into various behavioural aspects of sandwich panels was undertaken in recent times. This has resulted in advanced design methods for local buckling, flexural wrinkling, creep, durability, etc (CIB, 2000). Despite this, one particular area of sandwich panel behaviour which requires further research is the pull-through strength of connections in sandwich panels.

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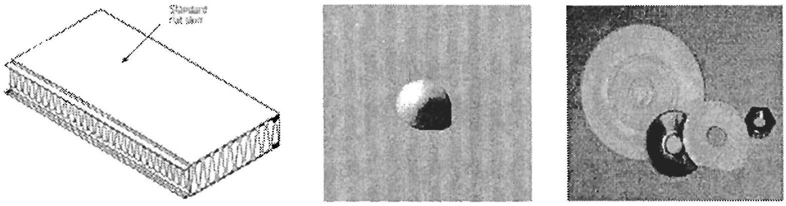


Sandwich Panel | Mushroom fastener | Mushroom Head Components

Figure 1. Sandwich Panel and its Fasteners

This research project was therefore undertaken to gain an understanding of the pull-through behaviour of connections in sandwich panels with polystyrene foam core, to identify the parameters that affect the pull-through strength and to develop a design equation. Both large scale and small scale tests were used for this purpose. Large-scale tests involved the use of an air box while the small-scale tests involved the direct application of a load to the fastener of the sandwich panel. This paper presents the details of this investigation and the results.

PULL-THROUGH STRENGTH OF SANDWICH PANELS

Screws or bolts are used to fix sandwich panels to their supports. Screws are used for panels up to 125 mm thick while bolts are used for thicker panels up to 300 mm. In the case of bolts, a large washer and nut are used at both ends. The fasteners used in Australia have a mush room head to reduce condensation and ice formation on the external face of the panels (see Figure 1). The main difference between the mush room head and traditional nut-washer arrangement is the use of a plastic cap.

Fasteners are subjected to a variety of loads including tensile forces from wind uplift and temperature differences between the faces. Shear forces can also develop due to other loading actions. Hence various failures can occur at the sandwich panel connections, namely, yielding of the inner panel or support structure, shear or pull-out or pull-through of the fastener, delamination of the inner face and core failure. However, this research concentrates on one of the critical failure modes, the pull-through failure of the fastener. Sandwich panels can be fastened through the panel thickness or the inner skin only. The pull-through failure occurs only in the case of through-fixing and hence this research has considered only the connections with fasteners through the entire panel thickness.

Pull-through strength is determined by the ability of the panel to prevent the fastener head from being pulled through the face of the panel into the foam core. Unlike in thin metal claddings where the screw fastener pulls through the sheeting, the fasteners will not pull through the panel thickness. The presence of a foam core will only allow the fastener to pull through the steel face and hence the pull-through failures in sandwich panels are unlikely to cause severe damage. However, the effect of foam core has not been researched well nor included in the relevant design formulae for the pull-through strength. At present, ECCS (1991) presents a design equation for the pull-through strength F_p in terms of only the face thickness t_f, washer diameter d_w, and tensile strength of steel face f_u with a material safety factor of 1.25.

$$F_p = 1.11\ t_f\, d_w\, f_u \tag{1}$$

The above equation is very similar to the design equation in AS/NZS 4600 (SA, 1996) for the static pull-through strength of cold-formed steel sheets. The only differences are: the coefficient 1.11 is replaced with 0.75 and the capacity factor is 0.5. Hence it can be stated that Equation 1 does not consider the strengthening effects of foam core.

The new European design document for sandwich panels (CIB, 2000) has now excluded Equation 1. The reason for this is not known, however, it may be due to the uncertainty in the accuracy of Equation 1. The pull-through strength of sandwich panel connections can be affected by a number of parameters such as steel face characteristics (thickness, yield strength and modulus of elasticity), foam core characteristics (thickness, shear and elasticity moduli, compressive strength), hole and washer diameter, fastener spacing, and span. Therefore a series of experiments was undertaken to investigate the pull-through strength of sandwich panels and their details are given in the following section.

EXPERIMENTAL INVESTIGATION

Test Program

This experimental investigation was aimed at investigating the following three key parameters: Steel face characteristics, Foam core characteristics, and Washer characteristics. Twenty-one small-scale and four large-scale tests were completed for this purpose. Large scale tests were undertaken to determine the adequacy of the small-scale tests in simulating the pull-through strength behaviour.

Sandwich panel faces made of G300 steel and two thicknesses (0.4 and 0.6mm) were used to investigate the effect of steel face characteristics. The measured tensile strength (f_u) and yield stress (f_y) of these steels are 413 and 441 MPa and 392 and 420 MPa, respectively. Two grades of expanded polystyrene (EPS), SL (standard to low) and M (medium) and two foam thicknesses (75 and 150 mm) were used to investigate the effect of foam core characteristics. The measured Young's modulus and shear modulus of these polystyrene foam cores are 3.44 and 1.72 MPa, and 5.4 and 2.7 MPa, respectively (Mahendran and McAndrew, 2003).

Three different washers were tested with a 9.5 mm diameter threaded rod and associated nuts. The standard mushroom head fastener was tested to compare the standard nut-washer fasteners and the preferred mushroom alternative, and to determine the effect the plastic portion of the mushroom head had on the pull-through strength. This was necessary because the mushroom head can degrade when exposed to sunlight, leaving only the 38.5 mm diameter washer inside the mushroom head to be effective. For this reason the second washer diameter was chosen as 38 mm to be equivalent to the internal washer in the mushroom head. The final washer diameter of 25 mm was selected to see the effect of varying the washer diameter. Washer thicknesses of 3 mm and 2 mm were selected for the 38 mm and 25 mm diameter washers, respectively. The mushroom head was not the main part of the test program and the traditional nut-washer combination formed the primary component. As mentioned above, the same threaded rod size was used in all the tests. Table 1 presents the details of the test program and test specimens.

Table 1: Details of Test Program and Test Specimens

Test No.	Face thickness (mm)	Face Grade	Panel thickness (mm)	Core Grade	Span (mm)	Washer Diam. (mm)
A	0.6	300	75	SL	1500	38
B	0.6	300	150	M	1500	38
C	0.4	300	150	SL	1500	38
D	0.4	300	75	M	1500	38
E	0.6	300	150	M	1200	38
F	0.4	300	75	SL	1200	38
G	0.6	300	75	SL	600	25
H	0.6	300	75	M	1200	38
I	0.6	300	75	SL	1200	38
J	0.6	300	75	M	1200	25
K	0.6	300	150	SL	1200	38
L	0.6	300	150	M	1200	25
M	0.6	300	150	SL	1200	25
N	0.4	300	75	SL	1200	25
O	0.4	300	150	M	1200	25
P	0.4	300	150	SL	1200	25
Q	0.4	300	75	M	1200	38
R	0.6	300	150	M	1200	Mushroom
S	0.6	300	150	SL	1200	Mushroom

Notes: All panels were 1200 mm wide. A to D : Large scale tests

Test Panels

It is important that the boundary conditions and overall behaviour of the panel represent that of the in-situ sandwich panels. Based on the deflected shape of the panels in both the direction of the span and normal to the span, a panel size of 1.2 m by 1.2 m was selected for the small-scale tests (Tests E to S). The size of the panel required the boundary conditions in the frame to allow free rotation at the edges while preventing them from translating in the direction of the applied load.

The selected size for the large-scale panels (Tests A to D) was 3200 mm long by 1200 mm wide with two 1500 mm spans. The width of 1200 mm was decided based on the standard panel width whereas the 1500 mm span was chosen to eliminate wrinkling failures. The small-scale panels were manufactured with the core joints away from the centre to prevent wrinkling. Similarly, the foam core joints were located away from the connection area for large scale panels.

Test Set-up and Procedure

Small-scale tests were completed using a purpose made frame shown in Figure 2. The frame was designed for maximum versatility and to allow the panel to behave in a manner similar to its in-situ behaviour. This required boundary conditions at the edges of the sandwich panels that allowed free rotation and prevent translation in the direction of the applied load. The frame was constructed of equal angles, which formed a C-shape to allow different size panels to be tested. The sandwich panel was placed inside the frame and the fastener was attached to the centre using the same procedure used in practice. A 10 mm hole was drilled through the centre of the panel and then a hole punch was used to open out the hole on the opposite side to the fastener. This enabled a plastic ferrule to be inserted before a 9.5 mm threaded rod was passed through the ferrule and attached using a traditional nut-washer fastener.

In order to allow the tests to be undertaken efficiently with the available facilities and to monitor the specimen behaviour more closely, the small-scale test set-up used a vertical panel with a load applied horizontally. The above frame was placed against two columns with the top and bottom being supported using 90 x 45 mm timber planks as spacers between the frame and columns (Figure 3). A hydraulic jack was used to apply the load to the fastener. A chain was used to attach the threaded rod to the load cell via an eyelet and D-clamp, respectively, with the load cell in turn attached to the hydraulic jack as shown in Figure 3. A deflection transducer was attached to the outside of the frame to measure the fastener movement relative to the frame. Load was applied to each fastener by manually pumping the hydraulic jack at a rate of 0.75 kN per minute until the fastener pulled through the steel face.

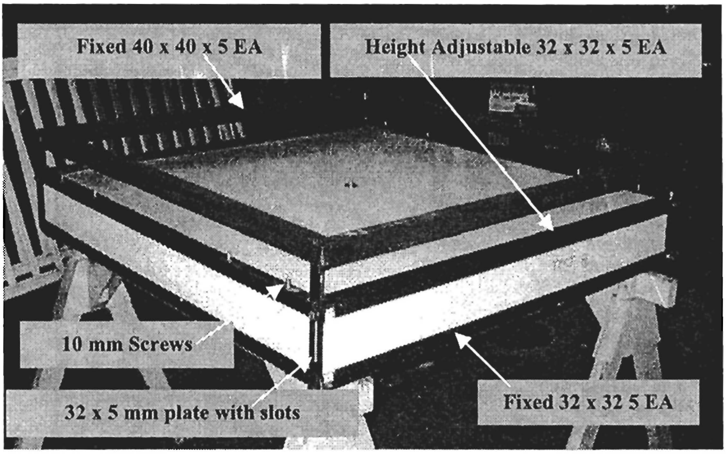


Figure 2: Small-Scale Test Frame

Large-scale tests were conducted in an air box shown in Figure 4. Each test specimen was placed in the air box by suspending it from timber supports at both the ends and the centre of the panel to simulate a two-span system. There was one fastener at each support with the central support fastener being the critical one. Before the panel was placed in the air box, the three fasteners were attached in a similar manner to that used for the small-scale tests. The threaded rods were then bolted to the timber supports using larger 50 mm washers. 50 mm washers were used on both sides at the end supports to prevent failure at these supports. At the central support, a load cell was placed with the threaded rod passing through both the timber support and load cell in order to measure the load in the critical central support fastener (see Figure 4).

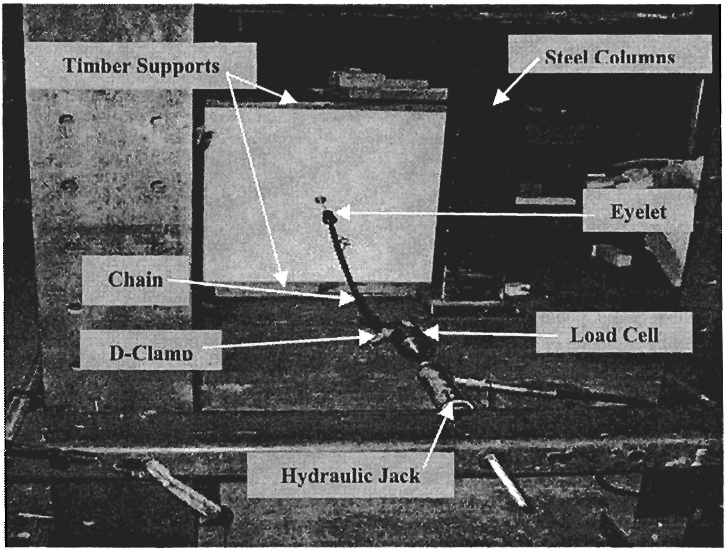


Figure 3: Small-Scale Test Set-Up

The air box was covered with a plastic sheet and the panel was tested by extracting the air from the air box using a large vacuum cleaner. This created a suction pressure under the panel at a rate of approx. 0.7 kPa per minute. This induced a tensile force in the fasteners and led to the fastener pulling through the sandwich panel face. Both the deflections and the induced fastener load were recorded until failure.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Small Scale Tests

Table 2 presents a summary of the results of 21 small-scale tests. The behaviour of all the specimens was similar at moderate loads. Slight dimpling of the panel surrounding the fastener was observed at approximately 0.5 kN. As the load was gradually increased, the dimpling remained stable until approximately 5 kN. This dimpling continued until the failure occurred suddenly via pull-through or wrinkling. In all the tests, considerable deflection of the fastener was noted.

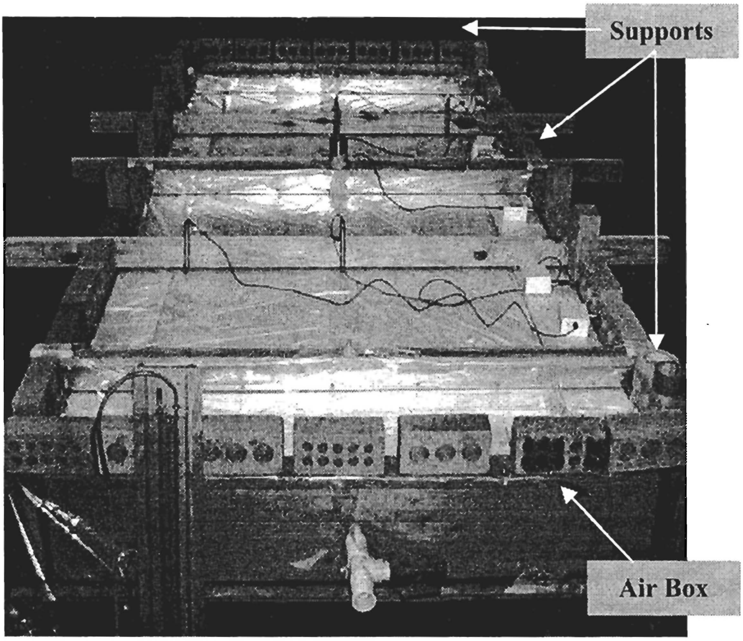
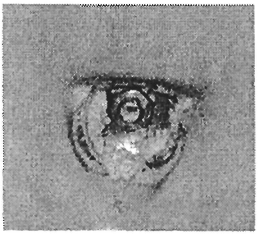
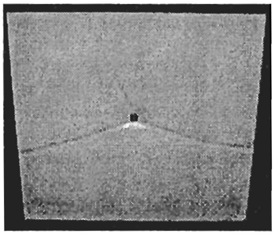


Figure 4: Large-Scale Test Set-Up

The observed dimpling and deflection behaviour demonstrates that the pull-through failure is initially ductile. The 38 mm washer and the washer inside the mushroom head were found to be deforming before pulling through the outer face. Inspection of the hole following each test found that pull-through failure occurred following the formation of three splits propagating from the edges of the hole (Figure 5). The formation of these cracks led to a slight reduction in load just prior to pull-through of the fastener. There were no visible signs of splitting around the fastener before the failure. The load at which splitting occurred was unable to be determined since the cracks formed underneath the washers. The pull-through failure occurred with the fastener pulling through the top face and 20 mm into the core material. The washers were considerably bent before the pull-through failure occurred (Figure 6).



Pull-through failure



Wrinkling failure

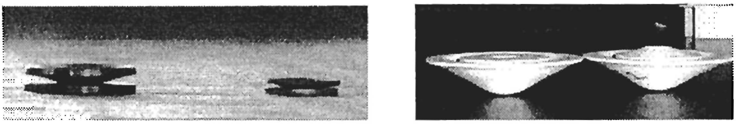
Figure 5: Failures of Small Scale Panels

Table 2: Small-Scale Test Results

Test No.	Failure mode	Failure load (kN)			
		Test 1	Test 2	Test 3	Average
E	Pull-through	12.77	11.22	-	12.00
F	Wrinkled	5.67	6.13	-	5.90
G	Wrinkled along joint	4.50	-	-	4.50
I	Pull-through	-	10.82	-	10.82
	Wrinkled	10.57	-	11.81	11.19
K	Pull-through	11.38	12.40	10.64	11.47
L	Pull-through	7.43	7.90	-	7.67
	Wrinkled	-	-	6.39	6.39
M	Pull-through	7.76	7.37	-	7.57
O	Pull-through	4.77	5.03	-	4.90
	Pull-through	-	-	8.14	8.14
P	Pull-through	5.51	5.00	-	5.26
R	Connection failure	13.00	-	-	13.00
R	Pull-through	-	13.00	-	13.00
R	Wrinkling	-	-	12.54	12.54
S	Wrinkling	10.16			10.16

Initial tests of the 75 mm thick panels showed wrinkling failures with no post-wrinkling strength. However, all the 150 mm sandwich panels with traditional nut-washer fasteners failed via pull-through of the fastener.

Test panels incorporating the mushroom head behaved in a similar manner to those incorporating the nut-washer fastener. The initial dimpling of the panel was less pronounced early in the test and remained smaller than the panels tested with the nut-washer fastener throughout the test. As the load was increased, the mushroom head itself began to deform, folding upwards at the sides and bulging on the underside of the mushroom head because of the deformation of the internal washer (Figure 6). This continued until one of the three events occurred. All events occurred at approximately the same load.



Washers Mushroom head

Figure 6: Deformation of Mushroom Head and Washers

The first panel tested in this manner failed when the entire mushroom head broke away from the threaded rod and was projected away from the panel. Inspection of the failed panel revealed that a crack had formed in the steel face, indicating that pull-through was about to occur. The second fastener was pulled-through the outer face. As the load was increased, a split developed in the plastic coating and the nut and washer inside the mushroom head were pulled from the plastic coating into the panel, while the plastic coating was projected backwards about 1000 mm from the test panel. The mushroom head was observed as being slowly pulled into the panel before suddenly pulling through in a similar manner to the nut-washer fastener. The third test panel failed by wrinkling.

Table 3 presents the results of four large-scale tests. Only two tests of panels with 0.6 mm thick faces failed via pull-through of the fastener (Figure 7). Pull-through failure occurred at the central support following large deflections of the panel. Three cracks had propagated from the hole, which allowed the fastener to be pulled a considerable distance into the panel. The panels with 0.4 mm steel faces failed by wrinkling rather unexpectedly. The reason for this is the presence of foam core joints.

Table 3: Large-Scale Test Results

Test No.	Failure mode	Fastener Failure Load (kN)	Failure Pressure (kPa)
A	Pull-through	13.40	6.93
B	Pull-through	15.38	7.97
C	Transverse wrinkle	7.35	3.81
D	Longitudinal wrinkle	Not reliable	

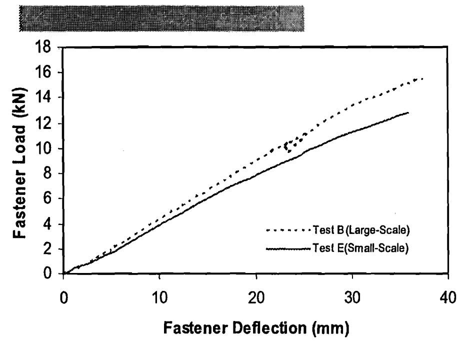


Figure 8. Fastener Load-Deflection Curves

ANALYSIS AND DISCUSSION OF RESULTS

This section presents the analysis and discussion of results reported in the last section.

Adequacy of Small-Scale Tests

The pull-through failure behaviour associated with dimpling and large deflections followed by a sudden pull-through of the washer was identical in both small scale and large scale tests as seen in Figures 5 and 7. However, the results of the large-scale and small-scale sandwich panels revealed that the large-scale results were on average 26% higher than the small-scale test results. These tests are: Test A (13.4 kN) versus Test I (10.8 kN); Test B (15.4 kN) versus Test E (12 kN). Load-deflection curves demonstrated a similar behaviour of small scale and large scale specimens up to a load of 6 kN, but they deviated beyond that load. The differences between the large-scale and small-scale test results are considered to be due to the inability of the small-scale test set-up to simulate the large-scale test behaviour due to approximate boundary conditions. This needs to be investigated further. Figure 8 shows the comparison of load-deflection curves from small and large-scale tests.

Comparison of the 38 mm Washer and Mushroom Head

The results of Tests R and E (13 kN versus 12 kN) show that the mushroom head is slightly stronger than the standard 38 mm washer (about 8%). Comparison of load-deflection curves indicates that the mushroom head provides a stiffer and more brittle connection. It was also observed that the ensuing dimpling of the face and deflection of the mushroom head was not as significant, thus providing limited warning of the imminent failure. The additional stiffness is due to the larger overall size of the mushroom head compared to the nut-washer fastener. It can be concluded that the plastic covering on the mushroom head reduces the dimpling and deflections and increases the overall stiffness.

While the tests using the 38 mm washer produced consistent results, the tests using the mushroom head provided mixed modes of failure. The mushroom head combination was initially tested on three identical panels (see Table 1). Each test failed at approximately the same load (13 kN) but in a different manner as mentioned earlier. The formation of a split under the mushroom head indicated that had the fastener not failed, the fastener would have pulled through. Test observations indicated that splitting occurs at the maximum load immediately prior to pull-through.

The above results indicate that the presence of the plastic portion of the mushroom head does not considerably increase the pull-through strength of the sandwich panel. The fastener will still be adequate if the plastic portion is degraded due to sunlight exposure.

Effect of Panel Thickness

Comparing the results of Tests I and K shows that the thicker 150 mm panels are 6% stronger than equivalent 75 mm thick panels although the load-deflection behaviour was identical in the early stages. This indicates that the pull-through strength of the sandwich panel increases slightly with increasing panel thickness. Thinner panels are likely to wrinkle while the thicker panels (100 mm to 250 mm) may be subjected to pull-through failures. Since pull-through failure only occurred through one face and the fastener was pulled about 20 mm into the panel in both the 75 mm and 150 mm panels, it is unlikely that the panel thickness has a significant effect on the pull-through strength. However, the test results show that panel thickness may have an effect. Therefore the effect of panel thickness should be included until more tests can be completed.

Effect of Face Thickness

Small-scale test results have shown that increasing the thickness of the face material greatly increases the pull-through strength of the sandwich panel. Comparing the results for Tests E (12 kN) and O (8.14 kN) demonstrate a 47% increase in the capacity. These results indicate that the face thickness of the sandwich panel has a significant influence on the pull-through strength of sandwich panels.

Effect of Washer Diameter

Test results show that the pull-through strength of connections increases significantly with the use of larger washers. This is confirmed by the results from Tests O, which were 4.9 kN for 25 mm washer and 8.14 kN for 38 mm washer. The larger and thicker 38 mm diameter washers endured greater deformation during testing than the 25 mm diameter thinner washers. This indicates that the stiffness of the washer could be a factor in the pull-through strength of sandwich panels. The mode of failure for the 25 mm washer appeared to be more of a punching failure than a pull-through failure. These results illustrate that further testing of washers with different thickness and diameter needs to be undertaken.

Effect of Foam Core Material

Comparison of results for sandwich panels with different grade cores produced inconsistent results and further tests are required. However, in most cases, sandwich panels with a stronger M grade core are moderately stronger than equivalent panels using a lower SL grade core. A comparison of results showed that the M grade panel (Test E – 12 kN) was 5% stronger than the SL grade panel (Test K -11.47 kN).

DEVELOPMENT OF DESIGN FORMULA

The results presented in the last section identify the parameters that affect the pull-through strength of sandwich panels. In this section the results are first compared with the available design equation (Eq.1). A new interim design equation is then developed for the pull-through strength of sandwich panels.

Adequacy of Equation 1

Table 4 presents the test results and compares them with the pull-through strength predicted by Equation 1. The failure loads in Table 4 were multiplied by a factor of 1.26 to allow for the inaccuracy of small-scale test results. They are listed in Table 4 as Modified Test Loads (MTL).

Table 4: Comparison of Test Loads with Predicted Design Loads

Test No.	Test Load (kN)	Modified Test Load (MTL)(kN)	Eq.1 Prediction F_p (kN)	Eq.1 F_p / MTL	Eq. 2 Prediction F_p (kN)	Eq.2 F_p / MTL
E	12.0	15.1	10.6	0.70	14.6	0.96
I	10.8	13.6	10.6	0.78	13.6	1.00
K	11.5	14.5	10.6	0.74	14.2	0.98
L	7.7	9.7	7.0	0.72	9.6	0.99
M	7.6	9.5	7.0	0.73	9.3	0.98
O	4.9	6.2	4.9	0.79	6.9	1.11
	8.1	10.3	7.4	0.73	10.4	1.02
P	5.3	6.6	4.9	0.74	6.7	1.01
			Mean	0.742	Mean	1.007
			COV	0.040	COV	0.046

Comparison of results in Table 4 shows that that Equation 1 in ECCS (1991) does not provide an accurate prediction of the pull-through strength of sandwich panels. The predicted loads were considerably less than the modified test loads with a mean of 0.74. This may be because the equation considers only the thickness and tensile strength of steel face and the washer diameter, and not the other influential parameters including the mechanical properties of foam core. Therefore an improved design equation including these influential parameters is required.

Improved Design Equation

Based on the results of this investigation, the following interim design equation is proposed for the pull-through strength of sandwich panels.

$$F_p = c\left[t_f d_w f_u \left(\frac{d_w}{t_w}\right)^{\alpha}\left(\frac{\sqrt{E_c G_c}}{E_f}\right)^{\beta}\left(\frac{t_p}{t_f}\right)^{\gamma}\right] \tag{2}$$

where:

c, α, β, γ = constants
t_f (mm), d_w (mm) and f_u (MPa) are as defined for Equation 1
t_w = thickness of washer (mm)
E_c = Young's modulus of the foam core material (MPa)
G_c = shear strength of the foam core material (MPa)
E_f = Young's modulus of the face material (MPa)
t_p = Foam core thickness (mm)

Equation 2 was developed by expanding Equation 1 to include the effects of the characteristics of foam core and washer. As shown earlier, t_f and d_w have a significant effect on the pull-through strength of sandwich panels. Hence, they have been included as two of the primary factors in the design equation together with f_u. Although the effect of f_u was not investigated in the tests, it was included as a primary factor as it is known to notably affect the pull-through strength.

The constants in Equation 2, c, α, β and γ were determined using Excel to be 1.92, 0.015, 0.055 and 0.059, respectively. The failure loads predicted by the new equation are compared with the test loads in Table 4. From the mean of the ratios of F_p to the Modified Test Load, it is evident that the interim design equation (mean = 1.007) is considerably more accurate than Equation 1 (mean = 0.742). The COV is also within the acceptable range of values. This indicates that the interim equation provides a good representation of the test loads.

It can be seen from Table 4, that with the exception of the first Test O value, all predicted loads are within 4% of the test value. The 11% difference for the first Test O value is due to the unexpected result where the panel with a weaker SL grade core had a higher pull-through failure load than the panel with a stronger M grade core. If this value is disregarded, the mean of the ratios is 0.992 and the COV is 0.019. This further confirms the accuracy of the proposed interim design equation. Due the variability in the material properties of sandwich panels, a capacity reduction factor in the range of 0.5 to 0.8 should be used with Equation 2. Further tests are required to improve the accuracy of the interim design equation.

CONCLUSIONS

This paper has described an experimental investigation into the local pull-through failures of connections in sandwich panels. Twenty five small-scale and large-scale tests were undertaken for this purpose. Test results have shown that in addition to the three key parameters of face thickness and strength and washer diameter, other parameters involving the foam core and washer characteristics also have an effect on the pull-through strength of sandwich panel connections. An interim design equation has been proposed by including all the relevant parameters. Further studies are required to improve the understanding of pull-through behaviour and the accuracy of the design equation.

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